Information Exploitation and Planning for a Sensor Web

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Outline

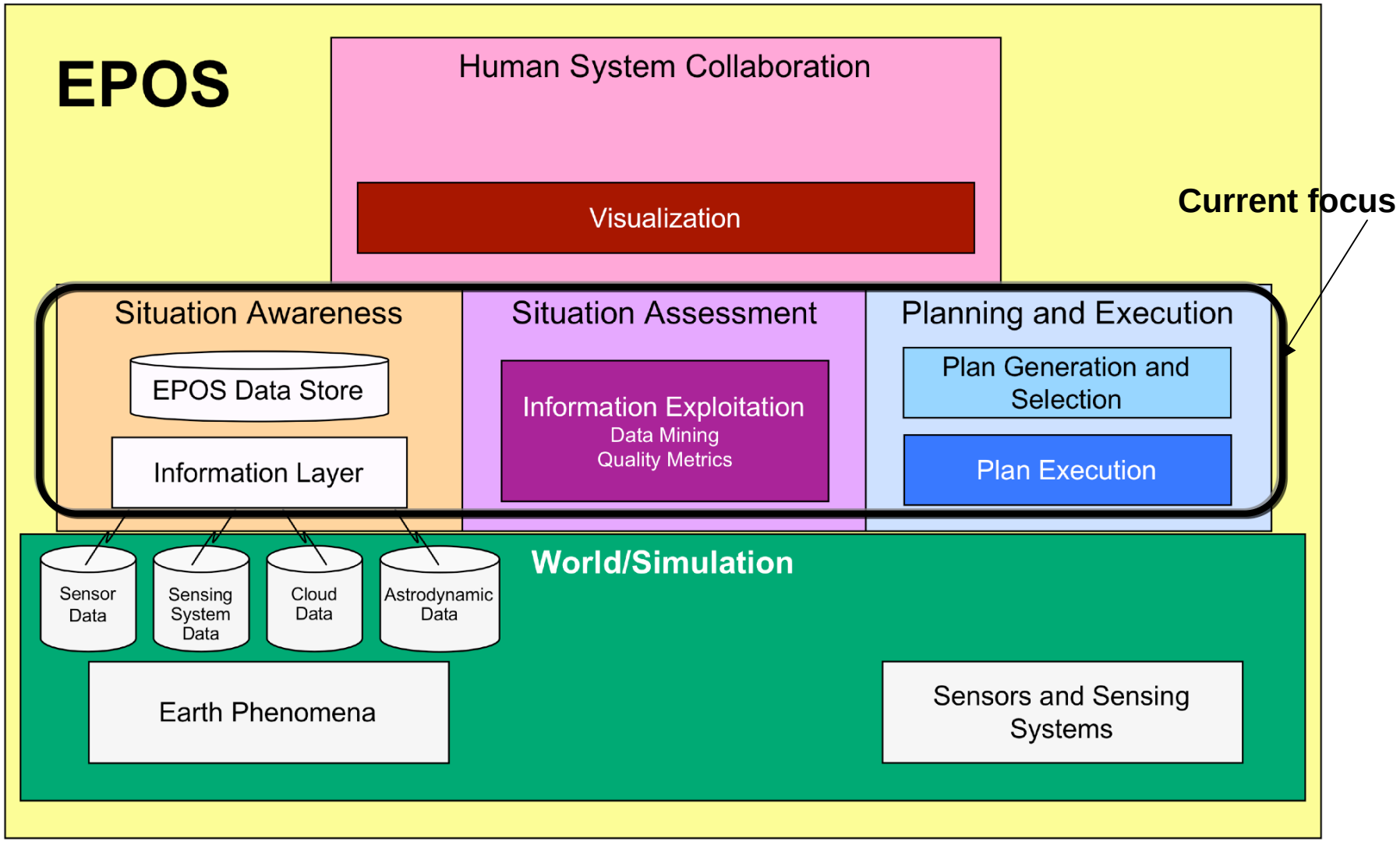
- **Overview**
  - EPOS functions
  - Web services
- **Information Exploitation**
  - Data mining for wildfire prediction
  - Stochastic Cloud Forecast Model analysis
- **Plan Generation and Selection**
  - UAV planner
  - EO-1 enhanced planner
- **Web Services objective**
  - Future concept of operations

Overall Objective of our Effort

Develop *information exploitation* and *planning* technologies that enable *coordinated asynchronous dynamic planning* for a *sensor web* to *maximize* the *value* of the observations for:

- **Science**
  - Multiplies the effectiveness of the operations of current sensor systems in gathering data for scientists
  - Can be used in the design of future missions, e.g., the decadal missions, to either decrease cost, increase effectiveness or both
- **Hazard detection, monitoring and mitigation to save human life and property, e.g.,**
  - Wildfires
  - Floods
  - Hurricanes
  - Harmful algal blooms

Earth Phenomena Observing System (EPOS) Functions



Goal: move software to web services software

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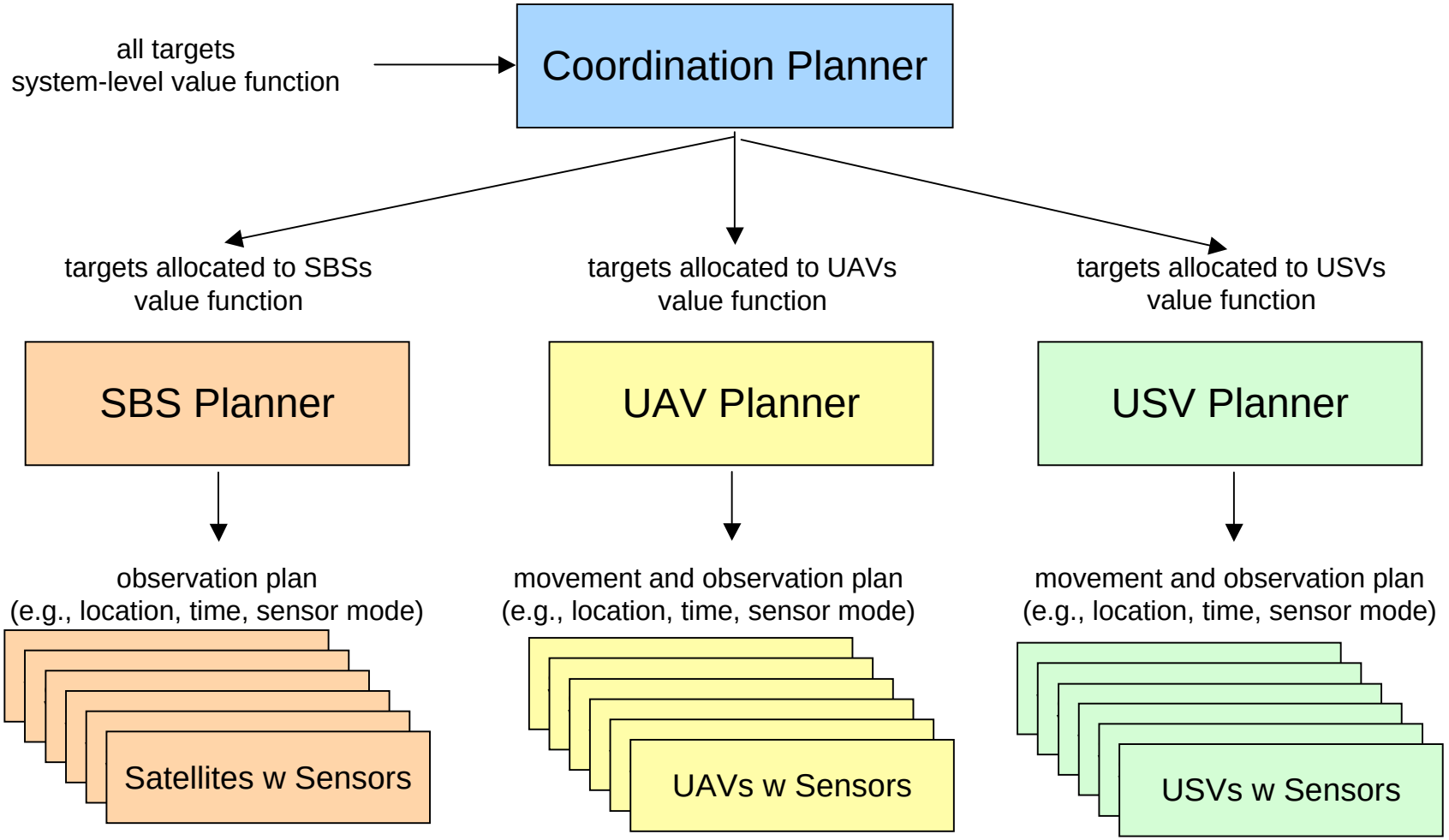
Functional Hierarchy for Sensor Web Planning

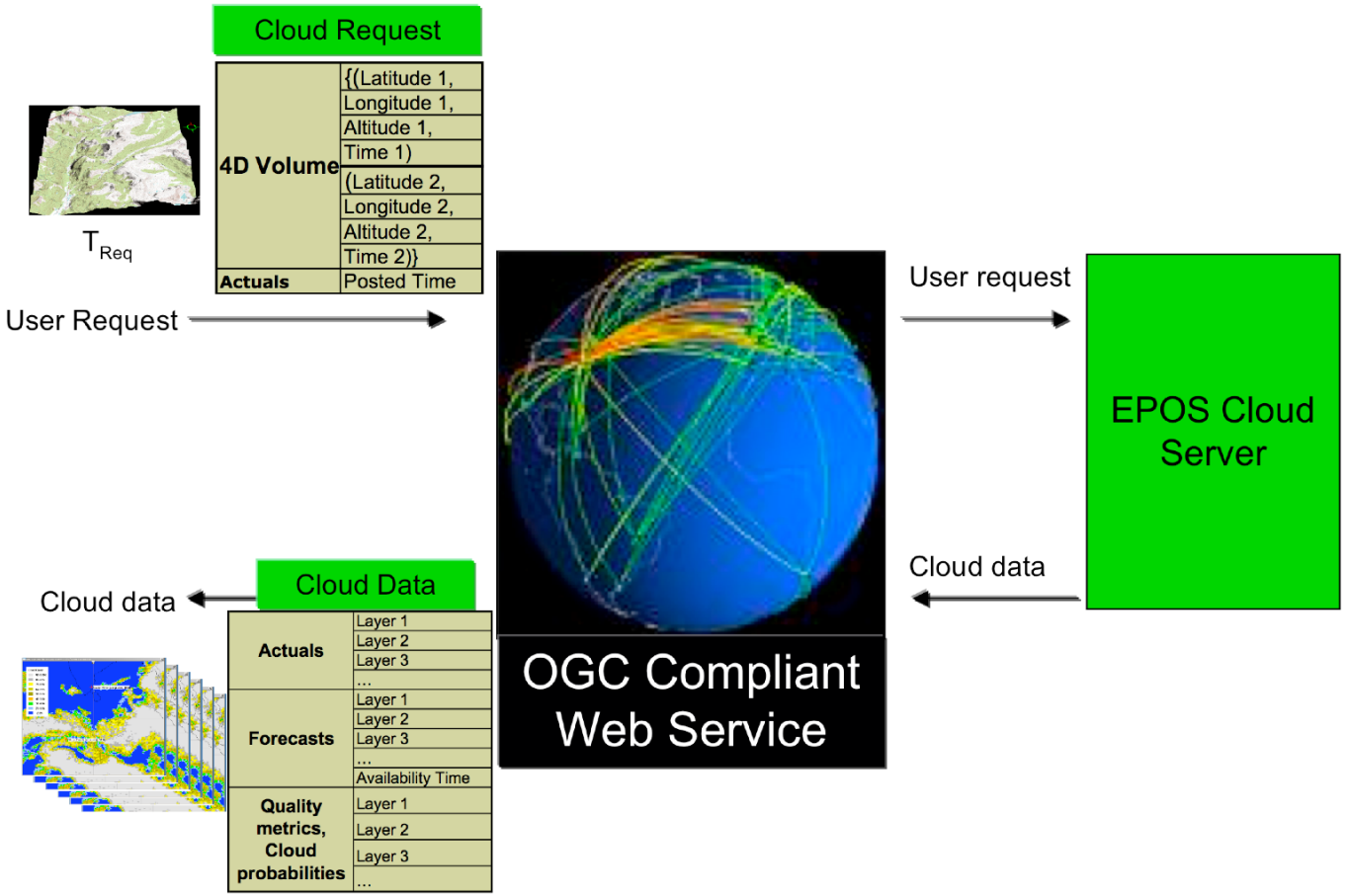
Plan Generation and Selection



SBS = space-based sensor
UAV = unmanned air vehicle
USV = unmanned surface vehicle

Cloud Cover Web Service

- **User specifies 4D volume of interest**
  - Requests forecasts or actuals
- **EPOS cloud server accommodates requests**
  - *Actuals*: after posting time for 4D volume data; immediately for historical
  - *Forecasts*: if forecast request too far into future, informs user when it will be available; immediately for current and historical forecasts



- **Outputs**
  - Layers of cloud cover data depending upon altitude range of request
  - Quality metric for forecasts
  - Cloud-free probabilities for forecasts

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Information Exploitation

Wildfire Prediction

Stochastic Cloud Forecast Model Analysis

Wildfire Prediction

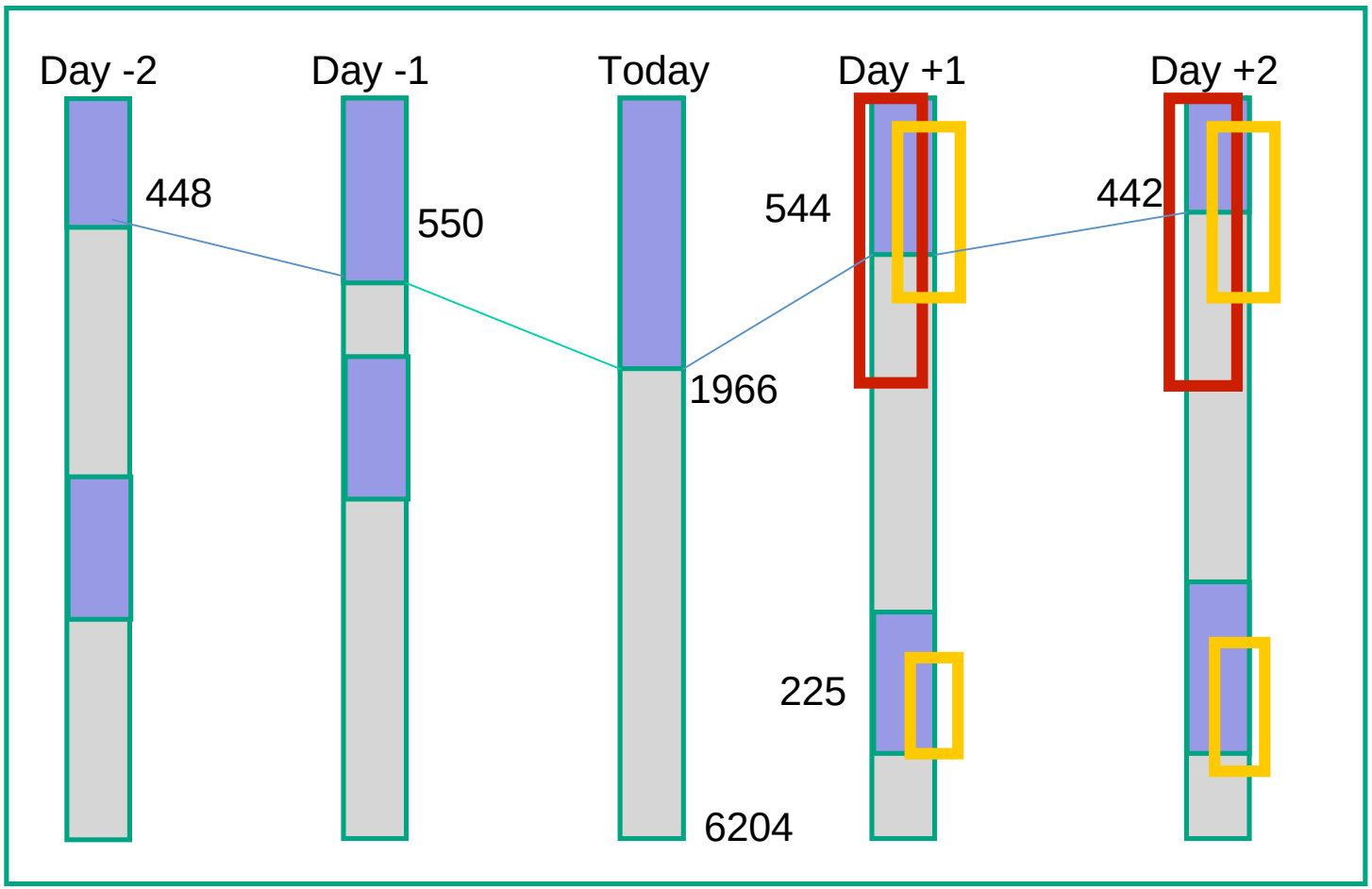
Data Based Predictive Modeling

- **Objective**
  - Develop ***data based*** predictive modeling approach that will improve projections of Earth phenomena, (e.g., fire, harmful algae bloom, hurricane)
  - Incorporate predictions in Earth observation planning missions
  - Apply models for real-time phenomena assessment and warning generation

- **Initial application: wildfires**
  - ***Goal was to****: predict which fires will develop into large and/or threatening ones based on several days of fire observations*
  - Build models using multiple years of archived observations from MODIS sensor, fused with weather data and land cover data
  - Evaluate advantages of fusion of multiple data sources
  - Different sensor systems have different lead times for tasking, some of which might be days in advance, e.g.,
    - The target location for an image to be gathered by ASTER has to be known several days in advance
    - A UAV used to image wildfires filed its initial flight plan 72 hours in advance

Predicting Next Day Fire

- A significant proportion of fires diminish in one day
- Small fires might become large



Human prediction

Model prediction

Large fire
(5 or more hot pixels)

Small fire or
No fire

Data record:

Day -2: fire info, weather	Day -1: fire info, weather	Today: fire info, weather	Land cover	Prediction

Human and Model Prediction Performance

- **Used directly, the model predicts correctly predicts no large (5 or more MODIS hot pixels) fires on Day +1 better than the human does**
- **Room for improvement in correctly predicting large fires**

			Day +1 state of the world	
			no large fire	**yes large fire**
Prediction	model	**no large fire**	80%	25%
	human		71%	26%
	model	**yes large fire**	20%	75%
	human		29%	74%

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Probabilistic Predictions

- **Probabilistic predictions from the model improves performance of large file predictions**
  - Reduces the number of false positives and increases the probability of correct prediction, e.g.,
  - If a cutoff of 0.90 or above is used, the percentage of true positives is very high
    - Covers 39% of the cases

Predicting D +1 Fire for Fires Active Today

Probability Range	True Positives (%)	Observations (%)
Human Performance	74%	-
1.00	100%	9
0.90-0.99	91	30
0.80-0.89	78	15
0.70-0.79	70	17
0.60-0.69	63	15
0.50-0.59	59	12

Stochastic Cloud Forecast Model (SCFM) Analysis

Cloud Cover Forecasts and Actuals

Cloud Cover Data Overview

- **We are currently automatically accessing cloud data from an Air Force Weather Agency server 24/7**
- **Current cloud data (WWMCA = World-Wide Merged Cloud Analysis) is received every hour**
- **Forecast cloud data (SCFM = Stochastic Cloud Forecast Model) is received every six hours, approximately 1.5 hours after the nominal time of the forecast**
- **We process the data and store in the EPOS Cloud Server**
  - Queries by visualization, information exploitation and planning allow access to any of the current or forecast data sets
- **We have been testing various measures of forecast quality to improve the use of the SCFM forecasts – the major ones:**
  - Forecast Quality Metric: previously reported analysis indicated its use is best as an aid to non-real-time scheduling
  - Direct estimation of the probability of a location being “cloud free” - initial results indicate a 10% increase in cloud free scenes
    - Cloud free = cloud cover less than 20%

Results from Ongoing EO-1 Operations Using EPOS

Evaluation period	January 2 - September 30, 2006 (271 days)	October 1, 2006 to March 29, 2007 (177 days)	March 30 to August 26, 2007 (153 days)	Aug 27 to April 20 2008 (237 days)
Total number of orbital revolutions with a scheduling scene	3750	2577	2117	3280
Total number of opportunities for target picks	396	179	220	375
Total number of alternate targets picked by EPOS	61	49	66	117
Total numbers of our picks that EO-1 actually imaged	55	43	61	94
Number of successful picks (less cloud cover over EPOS pick)	47 (out of 61)	37 (out of 49)	51 (out of 66)	105 (out of 117)
Number of unsuccessful picks	14 (out of 61)	12 (out of 49)	15 (out of 66)	12 (out of 117)

81.9% **success rate overall for EPOS picks**
89.7% **success rate this time period for EPOS picks**

Benefits from Using SCFM and EPOS Metrics

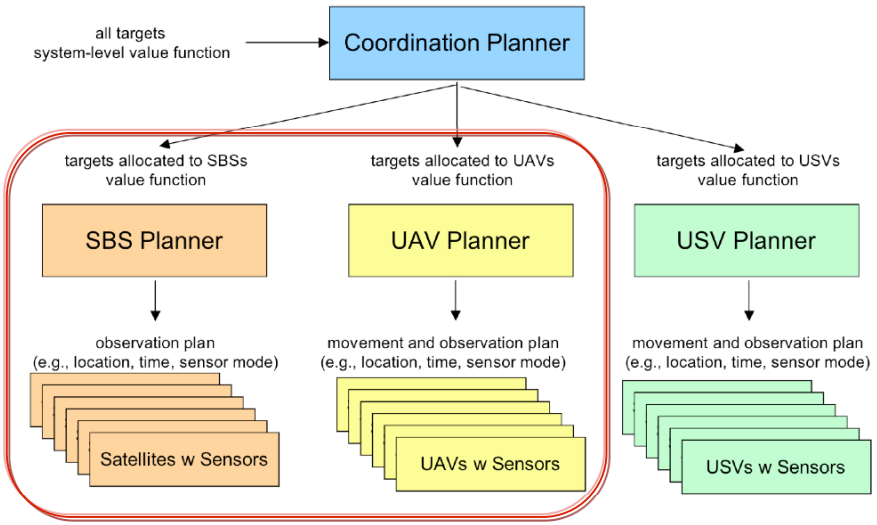
Number of simulated 24 hour periods:	**121 (1/1/07 to 12/30/07 at 3-day intervals)**
Total number of day and night passes (including fractional passes):	**3660**
Number of Rule 0 (random) selections for which WWMCA is ≤ 20% | WWMCA is available:	**1352 / 3382**
Number of Rule 1 selections for which WWMCA is ≤ 20% | WWMCA is available:	**1916 / 3284**
Number of Rule 2 selections for which WWMCA is ≤ 20% | WWMCA is available:	**2098 / 3288**

***Conclusions*:**

- **Using SCFM value to select between competing EO-1 targets (Rule 1) is *significantly better* than making a random selection (Rule 0)**
  - *Estimates the benefit of the use of cloud forecasts in EO-1 current operations*
- **Using EPOS estimate of P(C ≤ 20%) to select between competing EO-1 targets (Rule 2) yields nearly *10% more cloud-free scenes* than using SCFM value alone (Rule 1)**
  - *We are implementing this rule into operational use for EO-1, with an estimated 10% improvement in the number of cloud-free scenes*

Plan Generation and Selection

UAV Path and Observation Planner
EO-1 Enhanced Planner

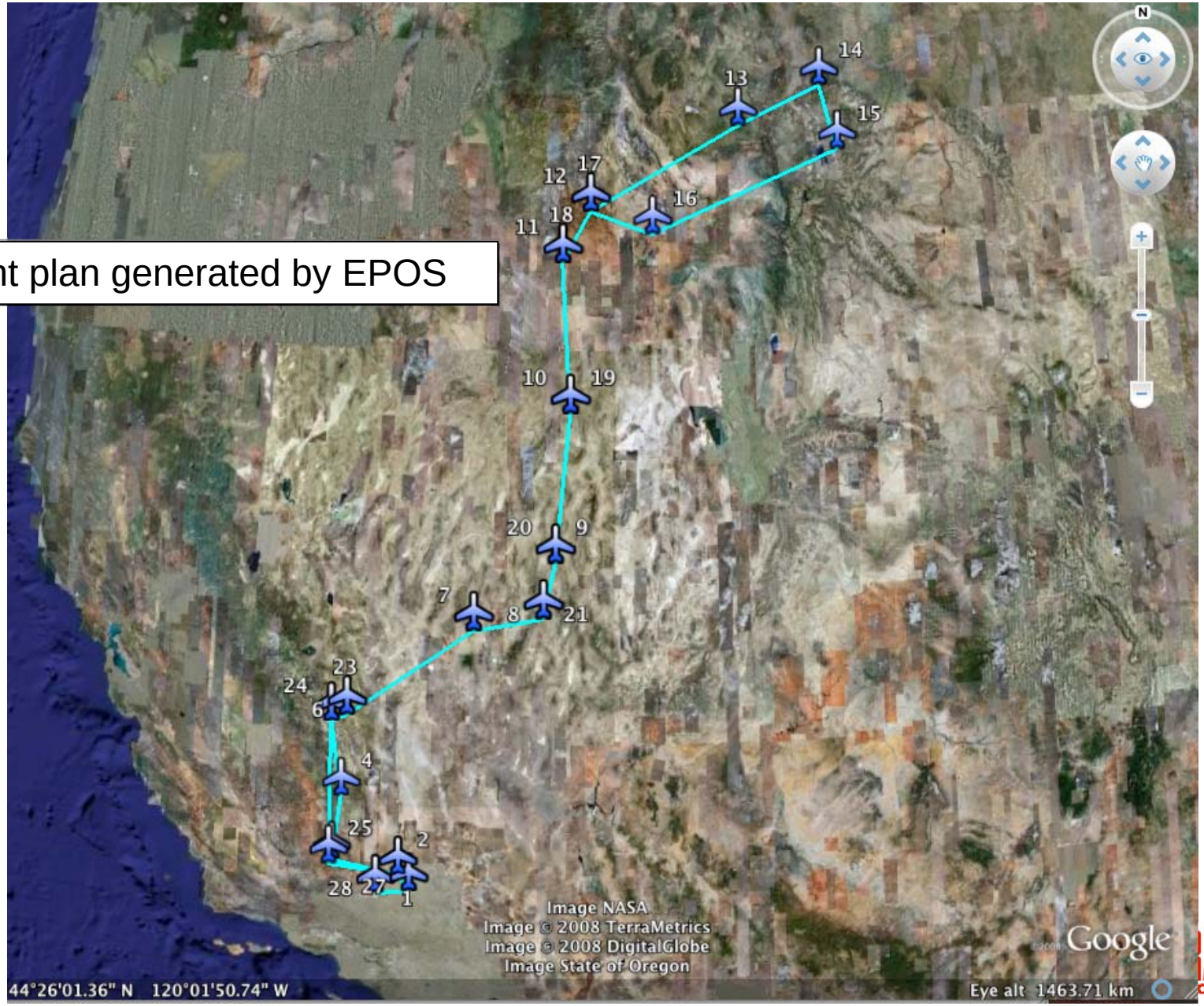


UAV Path and Observation Planner

The UAV planner work is equally applicable to manned aircraft

Single UAV Planner - 2007 Fire Demo Example

Flight plan generated by EPOS



Current: Multi-UAV Planning

- **Assumption: Two types of UAVs (or aircraft), all reusable**
  - Larger airframe, capable of high altitudes, long distances; one or two available from one base
  - Smaller airframe, limited altitude and range, higher resolution imaging; these have a mobile "base" and 5-6 can be launched from the same base; 2-3 bases exist

- **Critical element: *value function* for viewing targets**
  - Targets (e.g., locations, areas) have priorities and derived value; the goal is to gain the most value from viewing targets with the UAVs
  - There might be a non-linear value in viewing the same target multiple times with the same asset
  - There might be a non-linear value for the view duration
  - There might be a non-linear value in imaging targets with both types of UAV

Problem Formulation

- **General problem characteristics:**
  - All routes must be contained within a well-defined operational area, and avoid well-defined keep-out zones (population centers)
  - The output plan will be a route of waypoints and activities for each UAV
  - Additional detailed routing may also be done as a post-processing step
- **Model characteristics:**
  - UAVs will be assumed to have a constant speed when transiting between targets
  - UAVs will spend an amount of time at each target dependent on both the target and the UAV type
- **Model Inputs:**
  - Cruise speed
  - Image time
  - Climb/descend rate
  - Operational altitude range
  - Sensor FOV
  - Turn radius
  - Geometry of operational area and keep-out zones
- **Model Outputs:**
  - Decision variables representing which flight legs UAVs travel on (Path Plan)
  - Arrival time and duration at each target visited on plan (Observation Plan)
  - Total value to be gained from performing plan

EO-1 Enhanced Planner

Enhanced EO-1 Planning: Modeling

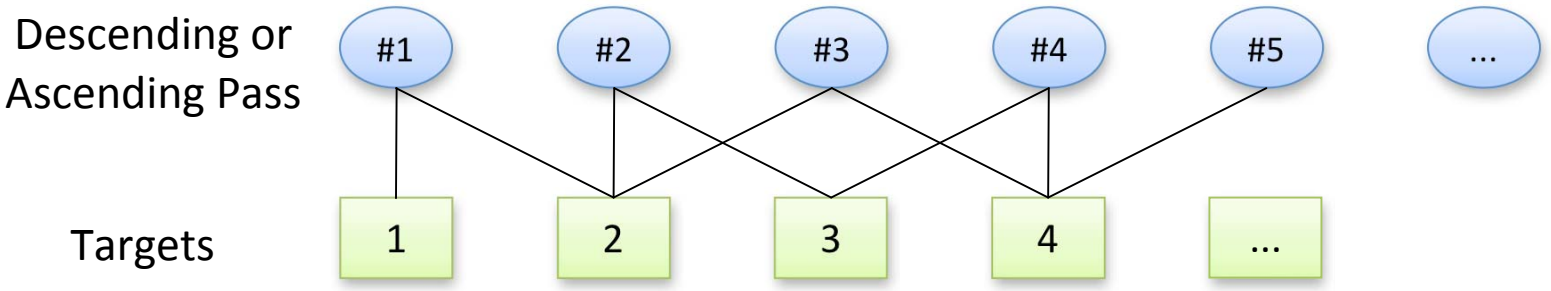
- **Inputs:**
  - The ephemeris for EO-1 at the start of a planning period
  - The list of target locations
    - Each target location has a score for successfully obtaining a clear image.
    - If multiple viewings are desired, the same location is repeated multiple times in the list. Each repeat can have the same score, or earlier viewings can be given larger scores.
- **Output:**
  - We use the ephemeris and SGP4* theory to compute, for each descending and ascending pass, what viewing opportunities exist
  - Then we look up the cloud forecast (up-to-date or historical-average)

Target	Score	Pass #1		#2		#3		#4		#5		...	
		Visible?	Pr(C)	V?	Pr	V?	Pr	V?	Pr	V?	Pr	V?	Pr
1	300	Yes	13%	N	-	N	-	N	-	N	-		
2	750	Yes	20%	Y	5%	Y	55%	N	-	N	-		
3	150	No	-	Y	12%	N	-	Y	18%	N	-		
4	900	No	-	N	-	Y	19%	Y	20%	Y	20%		
...	...	...	...	...	...	...	...	...	...	...	...	...	...

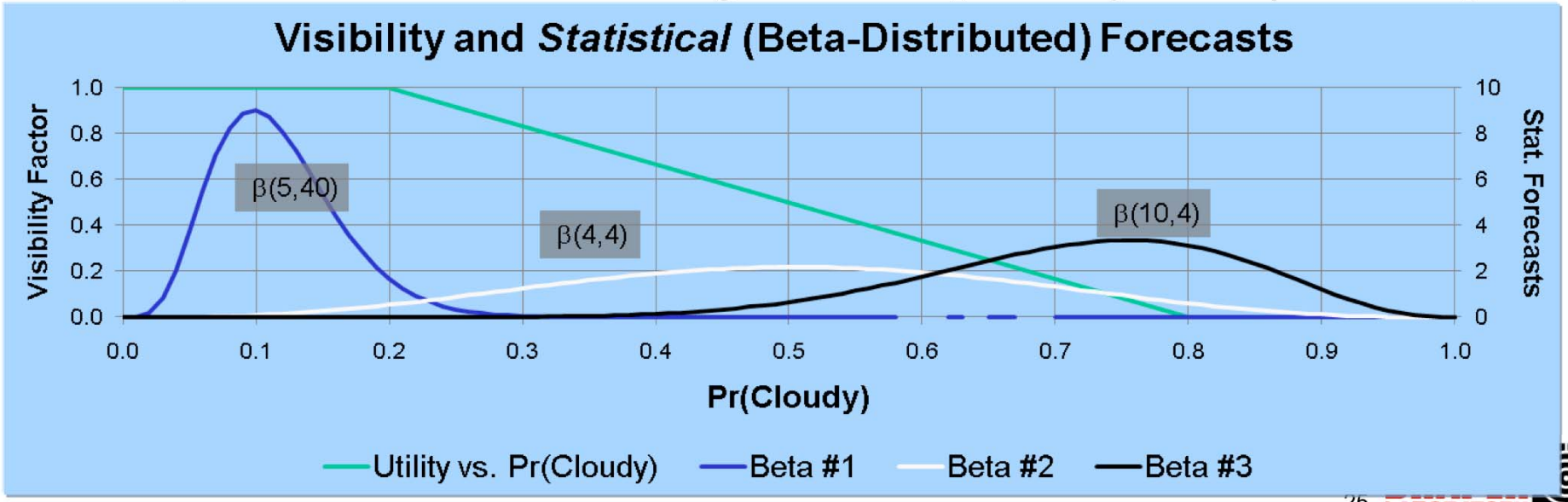
* Simplified General Perturbations Satellite Orbit Model 4

Enhanced EO-1 Planning: Assignment

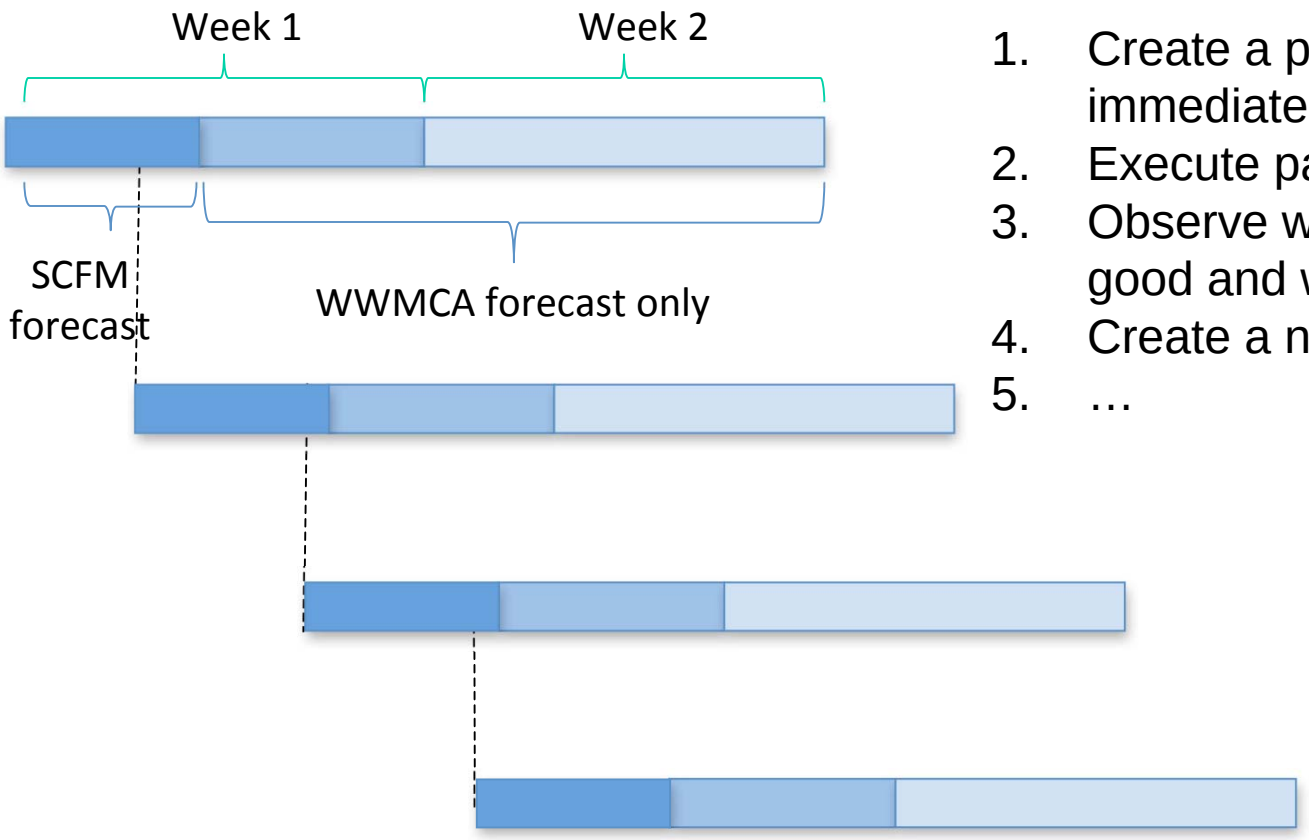
- **Construct and solve an assignment problem**
  - Exactly one target per pass – at most one pass per target



- **Expected value of scene = Target value · E[Visibility factor | Forecast]**



Enhanced EO-1 Planning: Rolling Horizon

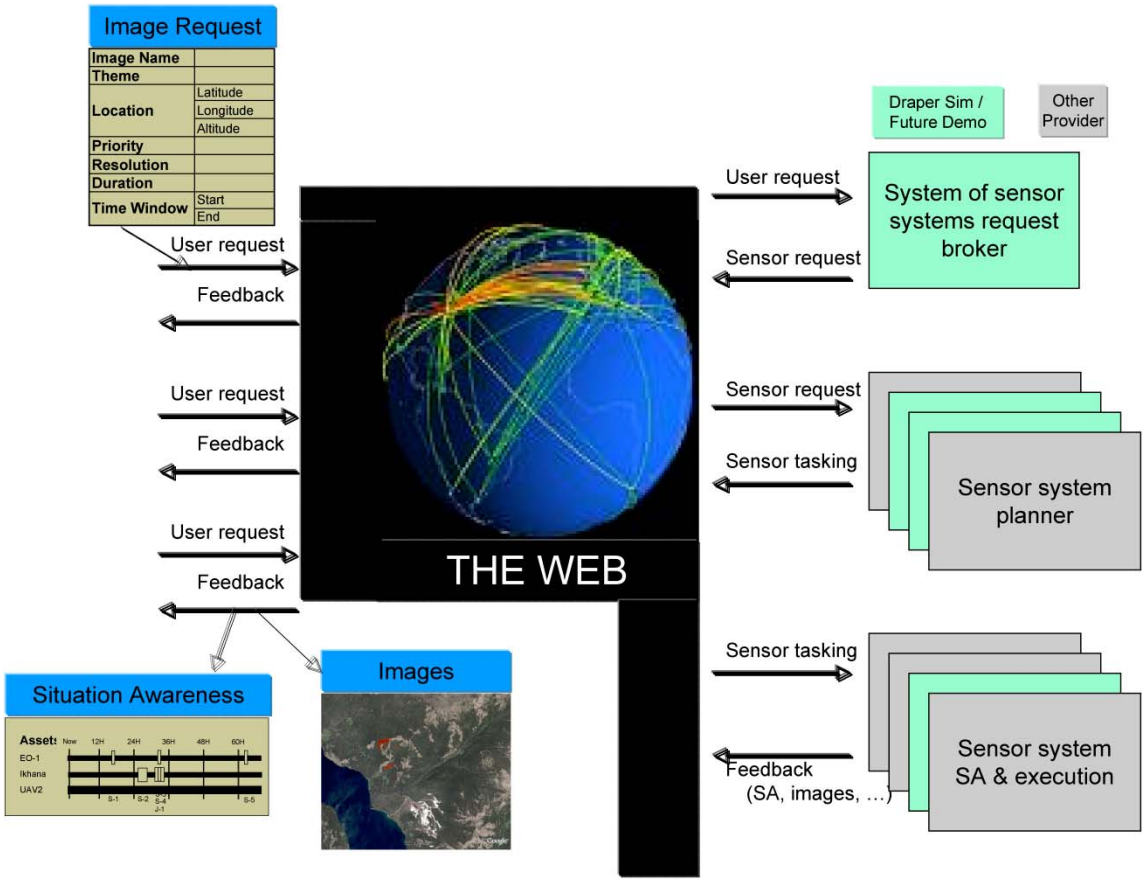


1. Create a plan including immediate and future decisions
2. Execute part of plan
3. Observe which images were good and which were obscured
4. Create a new plan
5. …

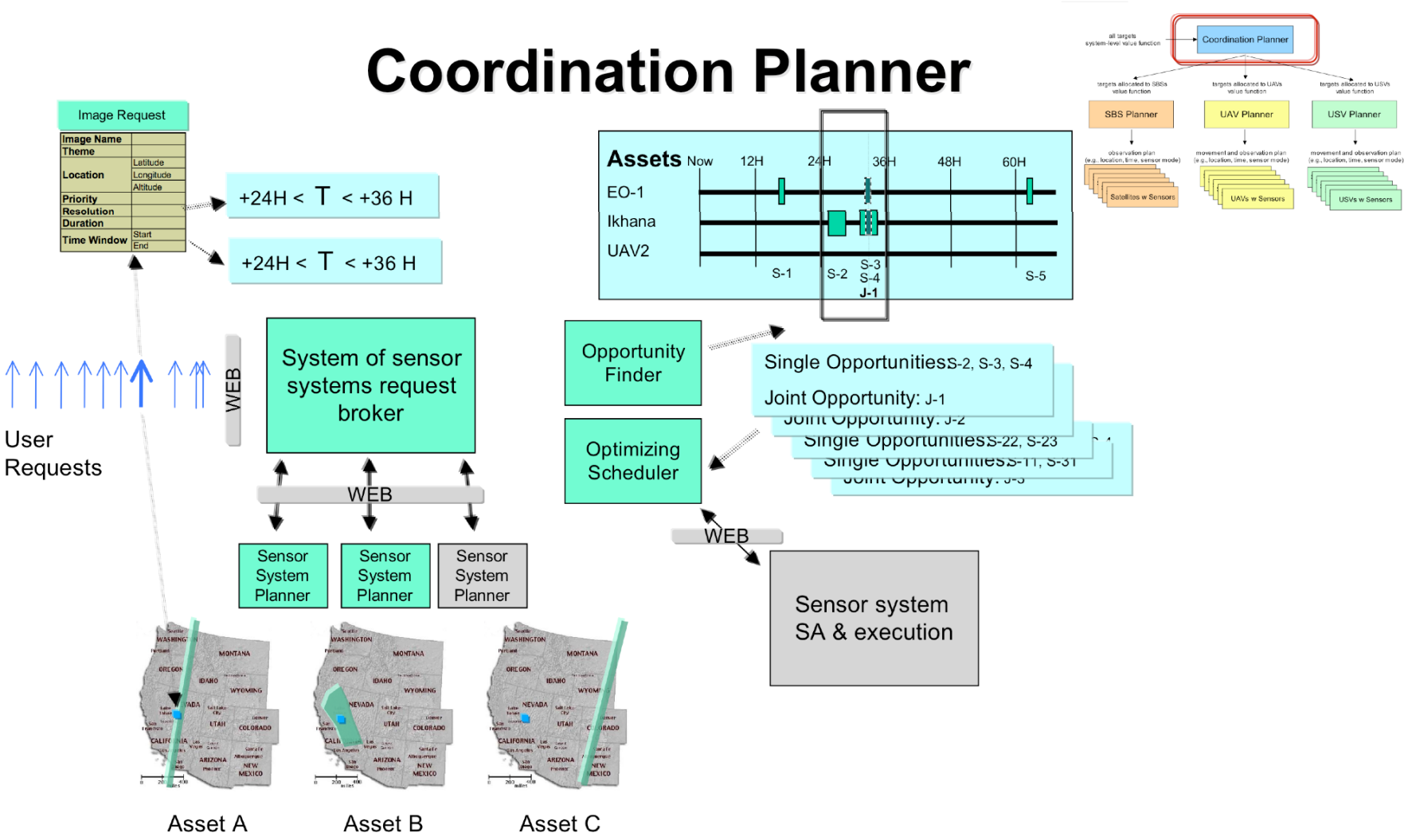
Objective: Web Services

Image Request Web Service

- **Vision for use of our Coordination Planner**
  - –Users request images, 3 coordinated services provide images and SA (Situation Awareness/Assessment)
- **Requests**
  - –Image requirements (type/theme, priority, location, resolution, time interval,…)
- **Processing**
  - –Identify collection opportunities, schedule collects, allocate requests to planners,
- **Results**
  - –Requested image (archive or just tasked), schedule of collection opportunities for user input

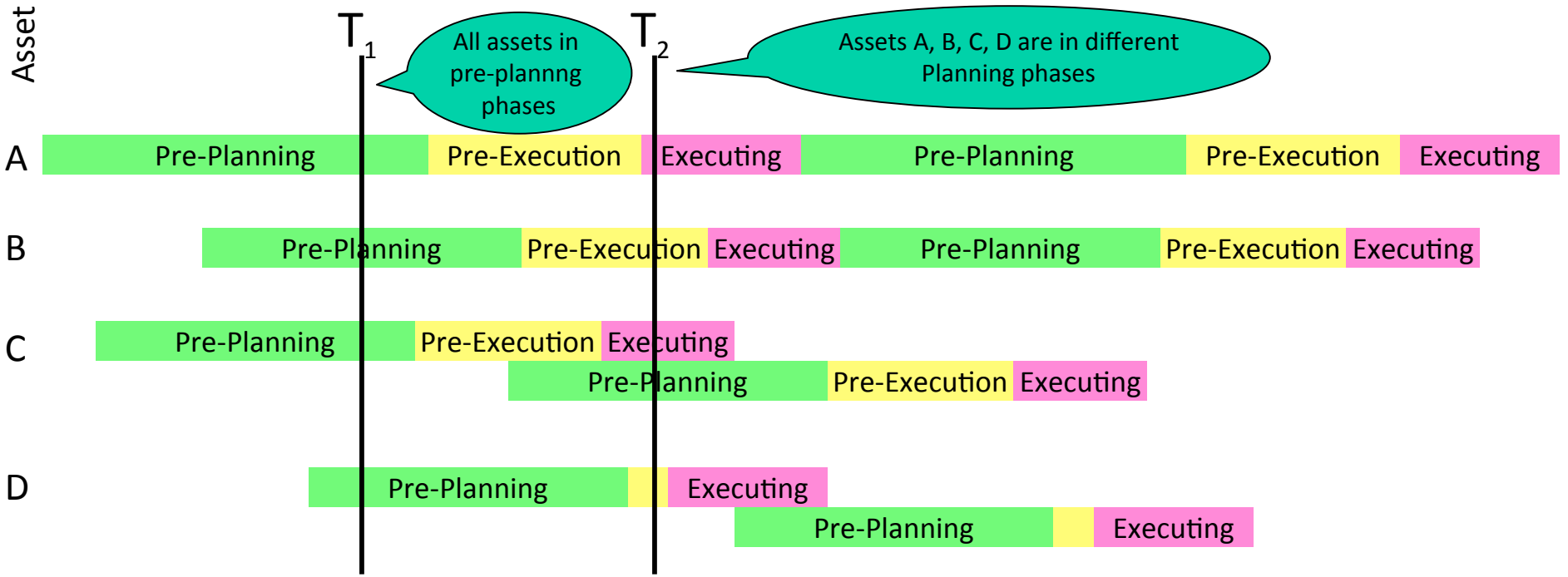


Coordination Planner



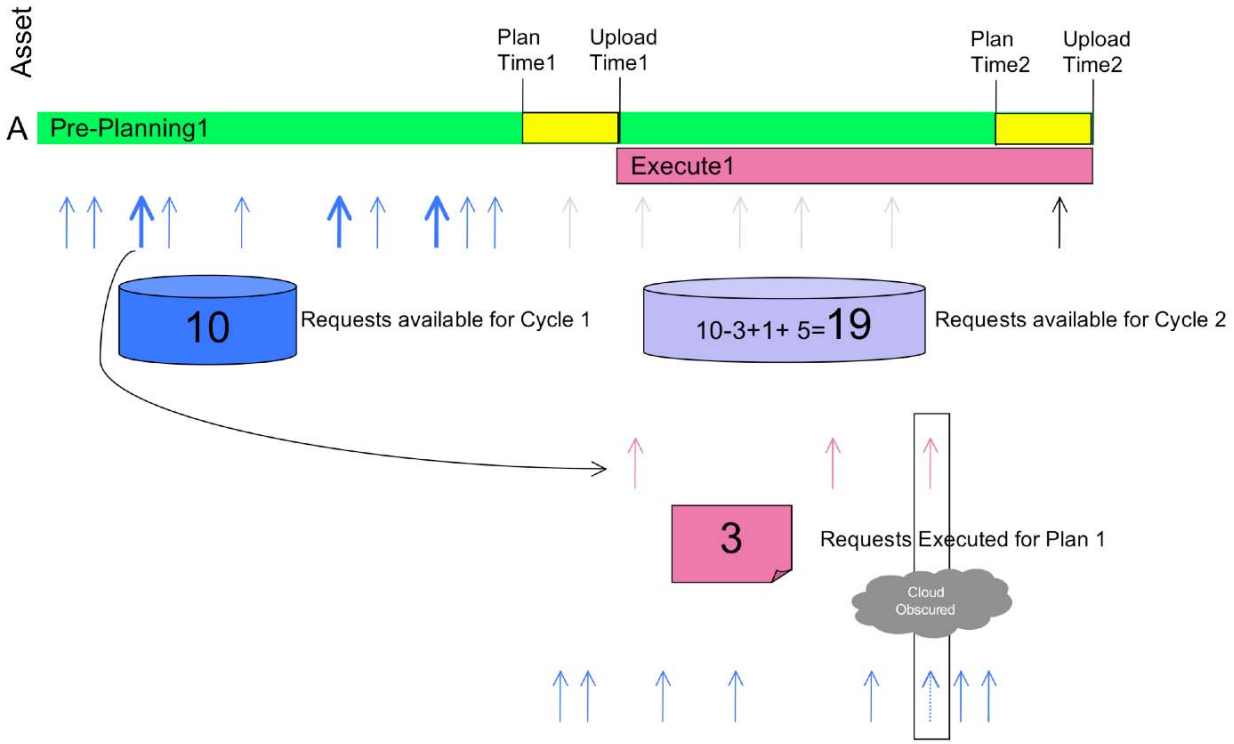
- Allocates each user request to one or more sensor system planners
- User request requirements are matched up to capability and availability of sensor systems under consideration
- Sensor system planners determine what opportunities for collection are available
- Coordination planner rolls up these opportunities, finds joint collects, and provides overall globally optimized schedule

Assets Have Asynchronous Planning Cycles



- **Three different periods for planning, each characterized by different rules on how new requests might get incorporated**
  - Preplanning
  - Pre-Execution
  - Executing
- **Assumptions**
  - Planning periods across the assets not necessarily synchronized
  - Periods of an asset's planning cycles may be overlapping
  - Plans may be generated at the end of a phase (e.g., Pre-planning), at fixed times within a phase, or based on events within a phase

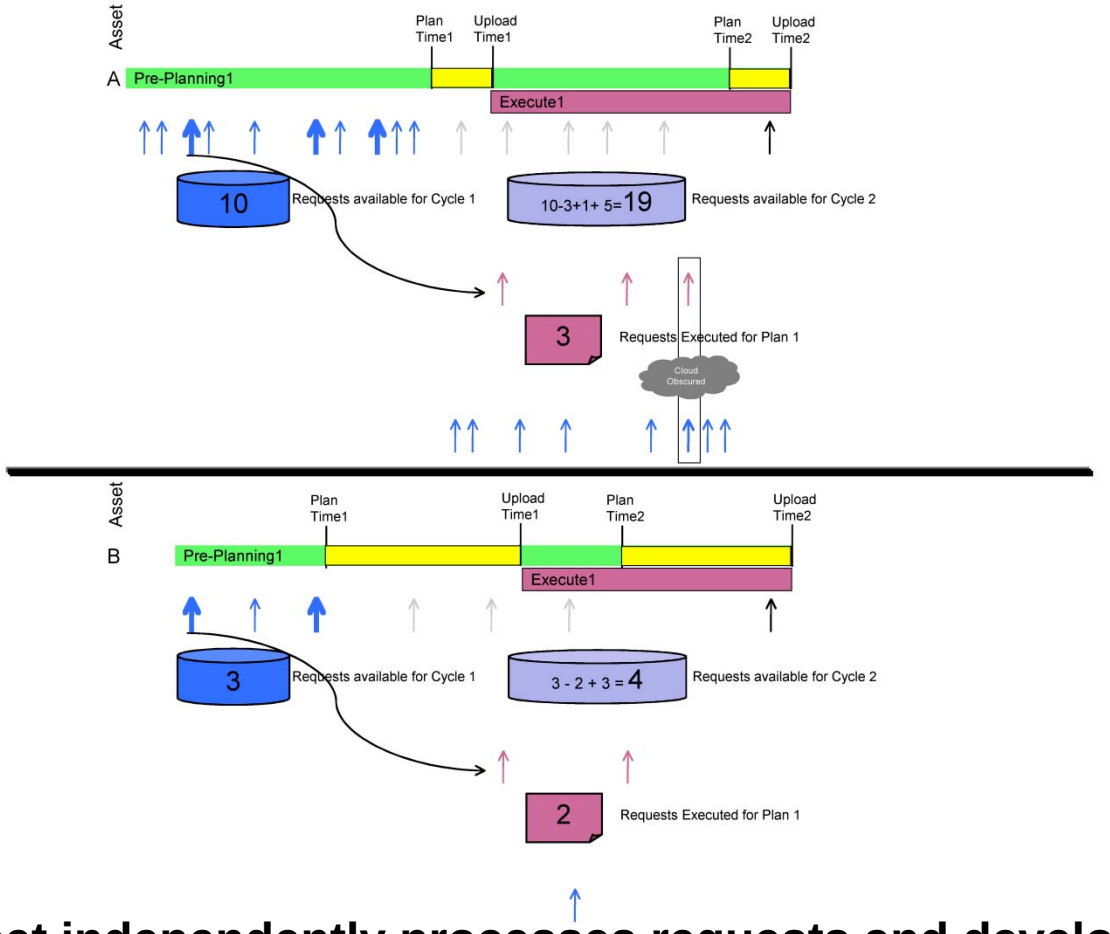
Planning Requests Over Time – Single Asset



A example to illustrate planning phases and cycles

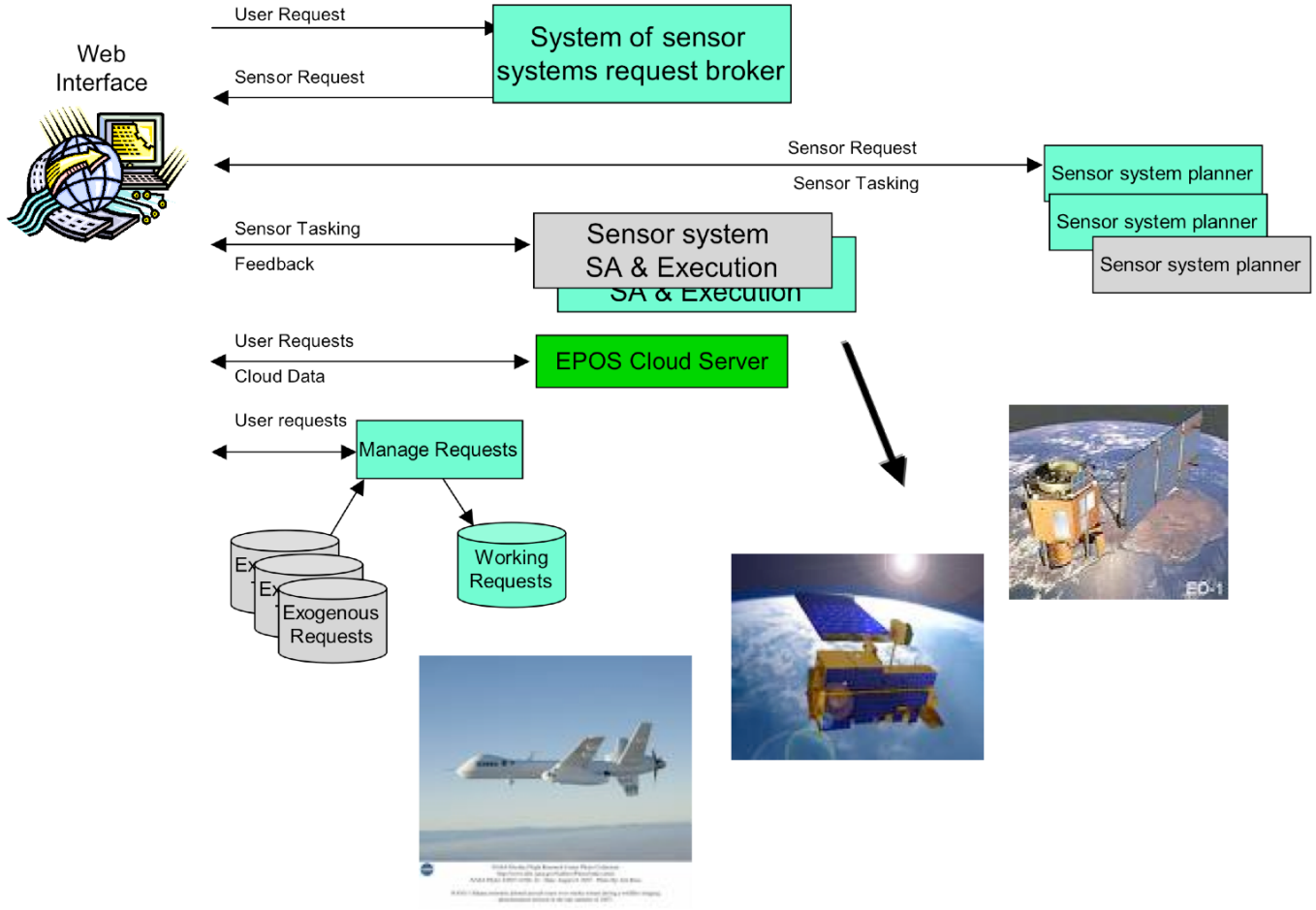
- **Requests accumulate during the pre-planning cycle – plan generated at end of cycle**
- **Next planning cycle will consider:**
  - Older requests not accommodated by first planning cycle (7 in example)
  - New requests that arrived after first plan generation (5 in example)
  - Planned requests that failed requirements (1 in example cloud obscured)

Planning Requests Over Time – Multiple Assets



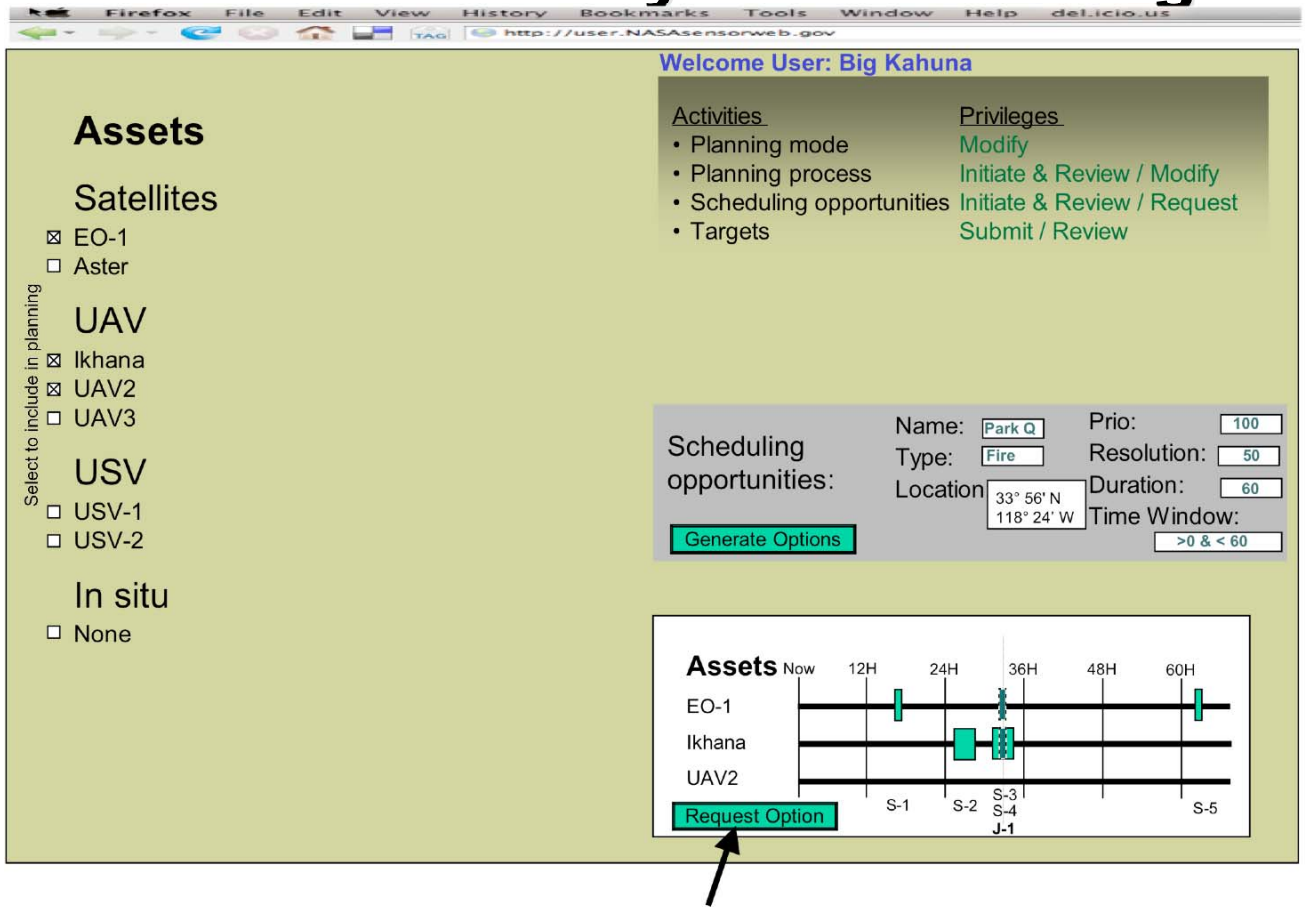
- **Each asset independently processes requests and develops plans**
- **Varying by asset**
  - Specific lengths of planning phases
  - Number of requests that can be incorporated in a plan
  - Rules for updating plans in pre-execution and execution phases

Architecture to Support Operational Concept



- **User interfaces to system via web, decoupled from where computations performed**
- **Leverage best-of-breed models and algorithms**
- **Design is scalable**
  - As sensor-web expands to encompass additional platforms
  - New user services are desired

User Interaction with System: Privileged User



- **Notional view of one part of a user web service interaction**
- **Users with different privileges accommodated by system**
  - The user in this example can
    - Select assets to be used in planning (a separate discovery service plays a role)
    - Request a list of collection options
    - Request a particular collection option, including a joint collect using multiple assets